

# A Second Kelvin-Helmholtz Timescale of Post Helium-Flash Evolution

Andrew Gould

*Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus, OH 43210, USA; gould@astronomy.ohio-state.edu*

## ABSTRACT

I show that after the “helium flash” abruptly ends its first ascent red giant evolution, a solar-type star is powered primarily by gravitational contraction of its helium core, rather than by nuclear fusion. Because this energy is released in the core rather than the envelope, the overall structure of the star, and so its luminosity, is driven toward that of a red clump star from its initial position at the tip of the red giant branch (TRGB). This occurs on a first (and well recognized) Kelvin-Helmholtz timescale  $t_{\text{KH},1} \sim E_{\text{env}}/L_{\text{TRGB}} \sim 10^4$  yr, where  $E_{\text{env}}$  is the thermal energy stored in the envelope and  $L_{\text{TRGB}}$  is the luminosity at the TRGB. However, once the star assumes the approximate structure of a clump star, it remains powered primarily by contraction for a *second* Kelvin-Helmholtz timescale  $t_{\text{KH},2} \sim E_{\text{core}}/L_{\text{clump}} \sim 10^6$  yr, where  $E_{\text{core}}$  is the thermal energy stored in the core and  $L_{\text{clump}}$  is the luminosity of a clump star. It is this second Kelvin-Helmholtz timescale that determines the overall pace of the moderately violent processes by which the star returns to nuclear-power generation as a full-fledged clump star. The reservoir of gravitational energy acts as ultimate regulator, providing whatever supplemental energy is needed to power  $L_{\text{clump}}$  and occasionally absorbing the large momentary excesses from helium mini-flashes. As this reservoir is gradually exhausted, helium fusion approaches the level of steady-state clump stars.

*Subject headings:* stars: fundamental parameters

## 1. Introduction

The transition from hydrogen-shell burning first ascent giants to helium-core burning clump stars is triggered by a “helium flash”. The underlying physics of the helium flash is so simple and so compelling that confidence in this conclusion is universal despite (until

very recently) a complete absence of physical evidence. Shell burning gradually deposits helium ash in the core of the giant, which forms a degenerate “white dwarf” with mass-radius relation  $R \propto M^{-1/3}$ . Just above the core, the hydrogen is compelled by the virial theorem to maintain a temperature satisfying  $(3/2)KT = (1/2)GM\mu_H/R$  where  $\mu_H$  is the mean molecular weight of the hydrogen gas. Hence  $T \propto M^{4/3}$ . The helium core is slaved to this thermostat. Since the core is supported by degeneracy pressure, it initially hardly expands as its temperature rises. Once the temperature rises to the point that heat is being generated faster than it can escape, a runaway sets in, since helium fusion scales  $\sim T^{40}$ . Eventually, enough heat is released to lift the degeneracy, which shuts off the runaway via both adiabatic cooling and reduced density  $\rho$ , since helium fusion scales  $\sim \rho^3$ . “Eventually”, the core becomes thermally supported and burns helium in a continuous manner, at which time it becomes a clump star. Since stars at the tip of the red giant branch (TRGB) and the clump are observed and are very well modeled according to the above picture, there can hardly be any doubt that the helium flash occurs.

Nevertheless, despite tremendous advances in modeling the post-helium-flash transition toward the clump, the underlying physics of this transition remains obscured beneath a welter of calculated details. It is known, for example that the transition takes of order 2 Myr, that during most of this transition, the star appears in most respects as a “normal” clump star, that it experiences a series of helium mini-flashes. This picture has been gradually developed over four decades, including particularly work by Thomas (1967), Iben & Renzini (1984), and Mocák (2008). Most recently, Bildsten et al. (2012) have extracted detailed predictions for acoustic signatures from their models of this 2 Myr period of transition. Very strikingly, three stars observed by the *Kepler* and *CoRoT* missions exhibit the predicted signatures, bringing the helium-flash triggered transition into the realm of observational astrophysics for the first time.

However, despite these advances, the basic reason for the  $\sim$  Myr timescale has never been given. And related to this, the main energy source powering the star’s luminosity has never been specified, although of course this energy source is fully encoded in the models. Here I resolve both issues.

## 2. Second Kelvin-Helmholtz Timescale

It is of course well known that the energy required to transition from a degenerate core to a helium-burning core at the temperature,  $kT_{\text{He}} \sim 9$  KeV, required to burn helium is given

by

$$\Delta E \sim \frac{1}{2} \left( \frac{GM_c^2}{R_{\text{degen}}} - \frac{GM_c^2}{R_{\text{therm}}} \right) = \epsilon_{\text{trans}} M_c c^2 \sim 100 \text{ Myr} \times L_{\odot} \quad (1)$$

where  $\epsilon_{\text{trans}}$  is evaluated by applying the virial theorem to the hydrogen thermostat before transition and to the core itself afterward,

$$\epsilon_{\text{trans}} \sim \frac{3}{2} \left( \frac{kT_{\text{He}}}{\mu_{\text{H}} c^2} - \frac{kT_{\text{He}}}{\mu_{\text{He}} c^2} \right) \sim 1.2 \times 10^{-5}. \quad (2)$$

Here,  $M_c \sim 0.5 M_{\odot}$  is the mass of the core at the helium flash,  $\mu_{\text{H}} c^2 = 0.58 \text{ GeV}$  is the mean molecular weight of the hydrogen mixture and  $\mu_{\text{He}} c^2 \sim 1.25 \text{ GeV}$  is the mean molecular weight of helium.

I now argue that it is the Kelvin-Helmholtz time derived from this energy,

$$t_{\text{KH},2} = \frac{\Delta E}{L_{\text{clump}}} \sim 2 \text{ Myr} \quad (3)$$

that is required for the core to adjust to steady-state helium burning, independent of the details of the transition.

The first point is that the helium flash must itself provide of order  $\Delta E$  in order to at least partially lift the degeneracy and so shut down the runaway helium burning. Most of this energy is injected on timescales of seconds or minutes, so that it may appear that in principle the transition could take place very quickly. However, quick examination of two limiting cases shows that this cannot be so.

In one limit, the runaway-shutdown is effective after injecting just a modest fraction of  $\Delta E$ . In this case, the rest of the energy must be supplied by something approximating core helium burning, which would require a time  $t_{\text{KH},2} = \Delta E / L_{\text{clump}}$ . In the other limit, the energy injection process overshoots the minimum energy required to lift the degeneracy. Such an overshoot must be less than a factor 2, or the star would blow up (which manifestly does not happen). In this case, gravitational contraction of the over-expanded core will power the star for a time  $\Delta E / \langle L \rangle$ , where  $\langle L \rangle$  is the mean luminosity of the star during this epoch.

This brings me to the second point, which is that in either of the above two cases, energy generation is taking place in the core, as it does in clump stars but not TRGB stars. This implies that, regardless of the energy source (nuclear fusion or gravitational contraction), the star as a whole will be driven toward the structure of a clump star, and hence toward a luminosity  $L_{\text{clump}}$ . This will take place on a timescale  $t_{\text{KH},1} = E_{\text{env}} / L_{\text{TRGB}}$  which is much shorter than  $t_{\text{KH},2}$ . Hence  $\langle L \rangle \sim L_{\text{clump}}$ , and thus the second case also implies a timescale

$t_{\text{KH},2} = \Delta E / L_{\text{clump}}$ . Thus, in both limiting cases, the timescale of transition from the TRGB to the clump is  $t_{\text{KH},2}$ .

The actual helium flash is likely to be a combination of these two extreme cases rather than intermediate between them. The flash is triggered off center because of neutrino cooling of the deep core. Hence, the outer part of the core is likely to receive more than enough energy to lift the degeneracy and the inner core too little. Both zones play important roles in the overall behavior of the star as it makes its transition.

The outer-zone overshoot implies that there is enough gravitational-contraction energy to power the star for  $\sim 1$  Myr at  $L_{\text{clump}}$ . Ordinarily, such an “external” energy source would tend to shut down nuclear fusion. That is, the nuclear burning is normally regulated by a balance between pressure and gravity: energy loss due to luminosity would lead to collapse of the star in the absence of energy generation, and this drives fusion to a rate commensurate with this loss. But if the energy is provided by gravitational contraction (as in a pre-main-sequence star) the pressure is not driven to the level required to sustain burning. Thus, the outer-zone overshoot by itself would tend to imply that helium fusion should be shut off, or at least heavily suppressed, during the transition.

However, if the degeneracy is not lifted near the center of the core, as seems likely from the asymmetry of the flash, then conditions here more closely approximate those of the pre-flash star. Since adiabatic expansion has cooled the core as a whole, this region is not immediately in contact with a “thermostat region” at the helium-burning temperature  $T_{\text{He}}$ , i.e., the role played by the hydrogen burning shell at the time of the flash.

## 2.1. Approach to Steady-State Clump

As contraction exhausts the reservoir of gravitational energy, the core must replace that source of luminosity with helium fusion. This fusion must take place near the boundary between the remaining degenerate inner core and the degeneracy-lifted outer core because heat transport is much more efficient in the latter (conduction vs. convection), making this the hottest part of the star. Fusion will go faster on the inner side of the boundary because the density is higher while the temperatures are the same.

There are only three things that can happen to energy generated in the degenerate core: 1) migrate outward and so contribute to the luminosity of the star; 2) migrate inward and so trigger deeper burning; 3) stay in the same region, heating it and so accelerating fusion, and thus triggering runaways leading to additional mini-flashes.

While it is not possible to capture the details of this process from this sort of general argument, the fact that conduction moves heat from warmer to colder regions implies that (2)+(3) must exceed (1). Since (1) is contributing a substantial fraction of  $L_{\text{clump}}$ , and since the remaining degenerate core mass  $M_{\text{degen}}$  contains only a small fraction,  $(M_{\text{degen}}/M_c)^{7/3}$ , of the original binding energy, the timescale for dissolution of the remaining degenerate core is smaller than  $t_{\text{KH},2}$ .

Because this timescale is shorter, in practice the dissolution of the remaining degenerate core will not take place *after* gravitational contraction is exhausted but rather simultaneously with it.

### 3. Comparison to Models

The above, very general arguments imply that independent of the details of the process,

1. The transition should take of order 1–2 Myr, during which the star should appear externally as a clump star.
2. The star should, at the beginning, be powered primarily by gravitational contraction, with helium fusion heavily suppressed. Then helium burning should gradually take over as the reservoir of gravitational energy is exhausted.
3. Helium fusion should take place primarily in mini-flashes at the beginning, and then gradually approach the continuous-burning rate of a clump star toward the end

Bildsten et al. (2012) have recently published detailed models of the transition period. Their calculations contain vastly more physics than the above simple arguments, and as a result make detailed predictions of acoustic signatures that should be observable in *Kepler* and *CoRoT* data, and arguably have already been observed. This is the first prediction of transition observables and hence the first real opportunity to test the details of models. However, independent of whether these details are correct, the above general points should hold, and they should hold for the Bildsten et al. (2012) models in particular.

All three “predictions” are “confirmed” by inspection of Figure 2 from Bildsten et al. (2012)<sup>1</sup>. First, the stellar luminosity remains fixed at almost exactly  $L_{\text{clump}}$  during the entire 2 Myr transition (orange line). Second, the combined power of the hydrogen and helium

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<sup>1</sup>I have placed these words in quotation marks because in fact I only formulated these “predictions” after seeing the Bildsten et al. (2012) figure. My actual intellectual process was to recognize that the principal features of this figure flowed from very general considerations, and did not depend in any way on the details of the calculation. In this *Letter*, I focus on these general considerations, which I believe could in principle have been elucidated without reference to specific models. But the fact remains that they were not.

fusion (green and blue lines) remains at a few percent of  $L_{\text{clump}}$  for most of the first 0.5 Myr, implying that most of the energy powering the total luminosity comes from gravitational contraction. Third, during this period, the core radius (brown line) shrinks from roughly 0.1 to 0.075  $R_{\odot}$ , which should release roughly 12 Myr  $L_{\odot}$  of energy, about enough to fully power a clump star for 0.3 Myr. Finally, the transition is punctuated by helium mini-flashes that briefly raise the core luminosity well above  $L_{\text{clump}}$ , which implies that time-averaged helium-fusion in the remaining degenerate core provides most of the luminosity not already generated by gravitational contraction.

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